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Emel'yanov I. G. [1], *Mironov V. I.*[2], *Kuznetsov A. V.*[3]
[1–3] Institute of Engineering Science, the Russian Academy of Sciences, Urals Branch,
[1,2] Ural Federal University,
Yekaterinburg, Russia

E-mail: [1]*emelyanov@imach.uran.ru*

VEHICLE SURVIVABILITY CALCULATION

Abstract. The article deals with multi criteria problem of the mechanical system in case of destruction of some of its elements. As an example, a dynamic contact between the gas-turbine locomotive GT1-h with an obstacle is considered. The purpose of this work is to obtain the information about the limit state of the locomotive cabin in terms of the parameters of the obstacles and the speed of the locomotive movement. This information is necessary for the design calculations, and is presented in a form suitable for engineering analysis. In three-dimensional parameter, space external impacts acting on the cab is defined as a hypersurface, which indicates that the structure is in the limit state. Such a surface determines the survivability of vehicles and specifies the safe operation of the locomotive cab in case of a collision with an obstacle. The calculations conducted have shown a significant effect of the area and location of load on the cabin survivability. It was concluded that it is necessary to strengthen the cabin to ensure the safety of the crew and the dashboard of the cab in case of an emergent collision with the obstacle of large mass and a high speed.

Keywords: gas-turbine locomotive, obstacles, dynamic contact, cabin survivability.

Емельянов И. Г.[1], *Миронов В. И.*[2], *Кузнецов А. В.*[3]
[1–3] Институт машиноведения УрО РАН,
[1,2] Уральский федеральный университет,
Екатеринбург, Россия

E-mail: [1]*emelyanov@imach.uran.ru*

ВЫЧИСЛЕНИЕ ЖИВУЧЕСТИ ТРАНСПОРТНЫХ МАШИН

Аннотация. Рассматривается многокритериальная задача поведения механической системы при разрушении отдельных элементов. В качестве примера анализируется внештатная ситуация динамического взаимодействия газотурбовоза ГТ1-h с препятствием. Цель работы состоит в получении информации о предельном состоянии кабины локомотива в зависимости от параметров препятствия и скорости движения состава. Данная информация необходима при выполнении проектных расчетов и представлена в виде, удобном для инженерного анализа. В трехмерном пространстве параметров внешнего воздействия на кабину построена поверхность перехода конструкции в предельное состояние. Такая поверхность ограничивает область безопасной эксплуатации кабины при случайном столкновении с препятствием. В результате проведенных расчетов выявлено существенное влияние площади и места приложения нагрузки на несущую способность кабины. Дано заключение о необходимости усиления кабины для обеспечения безопасности экипажа и приборной части при несанкционированной встрече с препятствием значительной массы и нарушении скоростного режима

Ключевые слова: газотурбовоз, препятствие, динамическое взаимодействие, живучесть кабины.

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1. Introduction

Transport safety is an important qualitative and quantitative component of the infrastructure of any level. On transport relatively often technogenic catastrophes occur. Typically, they result from the destruction of metal structures. The phenomenon of destruction of deformable solids still remains insufficiently studied section mechanics. Therefore it is important to find new approaches to the assessment of survivability of real mechanical systems with above permitted standard loading conditions. The paper discusses one possible approach by calculating area of safe operation of the locomotive cab upon a railway collision.

EN 15227: 2008 [1] gives some test collision scenarios. A consideration is made of a frontal collision of two identical trains at a speed of 36 km/h. A frontal collision of the train composition with a speed of 36 km/h with a stationary freight car weighing 80 tons is discussed as well. Also there is considered a collision of train composition with a low obstacle such as a car on a railway crossing, etc. These scenarios do not cover all the possible event of a collision. However, they make it possible to identify the boundaries of areas change various parameters that are not known yet.

In general, the formulation of the cabin design task looks easy. The strength and stiffness of the cab structure must be sufficient for the protection of personnel and dashboard of the locomotive when it hits an obstacle. Since allowed to destruction buffering elements and certain elements of cabin, this leads to the problem of cabin survivability. Exact solution in a rigorous formulation of such a problem is very difficult to receive. In addition to the unknown parameters of the obstacles in the problem, there is a number of complicating factors. Impact interaction of locomotive with an obstacle is above-standard load and thus change the properties of the material of construction. As a result, you may receive the plastically deformed elements and related computational difficulties. Vector external load on the cab is random, etc.

The proposed approach consciously used some simplifications. They involve the choice of material model and limit state of individual elements and the structure as a whole, contact model locomotive with an obstacle. The result is a calculation algorithm of survivability gas turbine locomotive cab. The calculations result in developing a surface defined by a combination of external factors that lead to the design of the cabin limit state.

2. Methods of research

The choice of research methods defined by a set of available computing resources, and includes a number of assumptions. It carries out the necessary mathematical formalization of the problem. Proposed are the substantiation material model and the failure criterion of the structural element. The computer program for calculating the stress state of the structure was selected. It determines the force of contact between the locomotive and the obstacle. An algorithm for solving the problem of the transition to the limit state design was developed.

2.1. Mathematical formalization of the problem

The behavior of the locomotive cabin as a mechanical system with external forces is determined by expression

$$Lu = q, \tag{1}$$

where q — an element of the space of input parameters Q, determined by an external impact, u — an element of the space U of output parameters, determining the state of the system, L — the operator which determines the correspondence between the elements of U and Q spaces, defining the method of calculation and taking into account the properties of the system. For mechanical design space Q can be defined as the force $F(t)$, applied at the time.

Based on the required strength of the locomotive cab the parameters of the space U in equation (1) can be represented as

$$U = \{\sigma_{ij}\}, \tag{2}$$

where σ_{ij} — stress tensor in the structure elements.

When any element of the structure is beyond the limit boundary Γ_u in the space U, then there comes a limit state design with the design can not lose or lose survivability

$$u(t) \le \Gamma_u. \tag{3}$$

For Q elements will also be corresponding with the safe operating area boundary Γ_q, which limits the safe operating area (survivability)

$$q(t) \le \Gamma_q, \tag{4}$$

where Γ_q — the boundary of the region in an n-dimensional space of the input parameters.

2.2. Model of the material and failure criterion of the structural element

The type of operator L in equation (1) is determined by the model material. In solving dynamic problems it is assumed that stresses change in the same way as in the static loading. Since locomotive collision with an obstacle takes place at high speed, the destruction of the structural elements will be of elastic and fragile nature. The destruction of the samples of material at high speed is fragile, and the dynamic yield stress is 30% higher than the static tensile strength [2]. Given this, a static calculation of the stress state of the structure takes place at linear operator L, that is with elastic deformation.

The power gas turbine locomotive GT1-h cab frame consists of a beam construction and bar elements shown in Fig. 1. The material elements of the cab (a plain carbon steel grade St3sp5) are characterized by the following properties: modulus of elasticity $E = 2 \cdot 10^5$ MPa, yield strength $\sigma_Y = 240$ MPa, ultimate strength $\sigma_{ult} = 500$ MPa, Poisson's ratio $\nu = 0{,}3$ and a dynamic yield stress $\sigma_{dY} = 650$ MPa. The force approach due to expression (2) and strength condition (3) takes the form

$$\sigma_i(t) \le \sigma_{dY}. \tag{5}$$

2.3. Computing tools for calculation of the stressed state of the construction

To determine the stress state of the railway structures upon impact different computing systems based on the finite element method are widely used now [3–6]. In this paper we used computer system ANSYS-15 [7], which was used for the determination of the stress state the cabin from a static force action [8]. Calculation is made with discrete increasing external force on a supercomputer "Uranus" IMM RAS Ural Branch.

From the statistics of accidents at crossings, and the design features of cab it follows that blow usually affects the frontal beam. A consideration is made of an external force using static horizontal force uniformly distributed along the length of the front beam of the cabin.

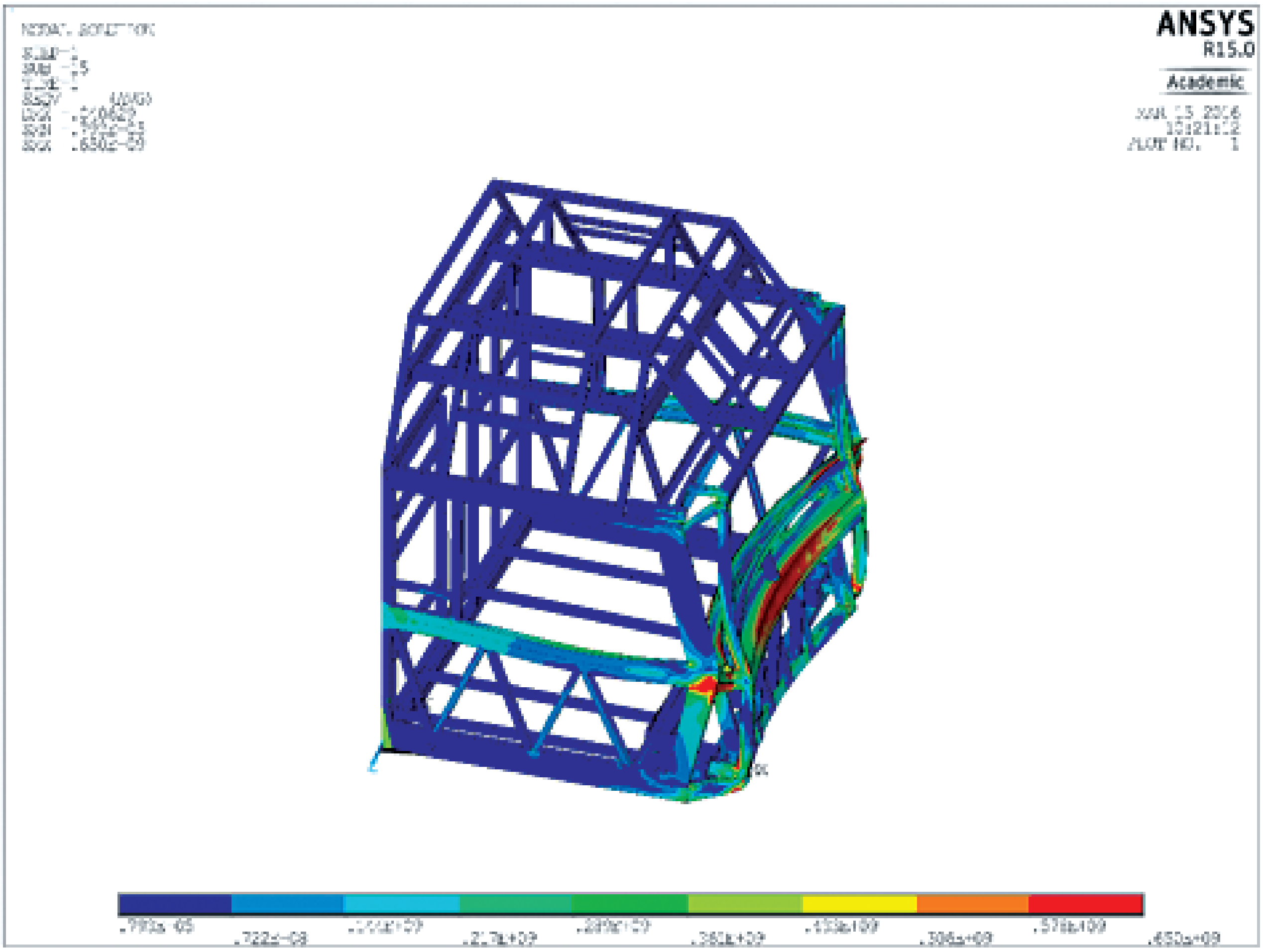

Fig. 1. Stress strain state of the cab in case of 100 % overlap frontal impact by the beams

2.4. The interaction force between the locomotive cabin and an obstacle

The interaction force between the locomotive cabin and an obstacle is defined as some elements from the Q (1). This speed for vehicle ν, the weight of the obstacles m_2, the friction force with moving obstacles surface F_f, the orientation of the obstacles relative to the front of the beam, the frontal area of the beam on which the impact occurs. The force will also depend on the stiffness of the cab itself c_c, the buffer structure c_b and stiffness obstacles c_{ob}. If the above parameters are known, the dynamic problem can be solved with the use of specialized computer complexes. Since the parameters of the obstacles are unknown, they can be assessed only according to the statistics of previous crashes, define the dynamic stress state of the cab, using the finite element formulation of the problem does not make sense. As in this case, the problem becomes with multiple-boundary and initial conditions. Consequently, to assess survivability of the cabin it is necessary to define cabins resistance in the space of possible obstacles parameters and vehicle.

To determine the force of interaction with the obstacle we use the expression [5]

$$F_{\max} = v\sqrt{cm_2} + F_f\,, \qquad (6)$$

where v — the speed of the locomotive, m_2 — the mass of obstacles, $F_{\max}$ — elastic interaction force, F_f — the force of friction with moving obstacles surface, c — equivalent stiffness of the cabin and obstacles, c is the equivalent stiffness similar to the series connection of a system of three spring is determined by the expression

$$c^{-1} = c_c^{-1} + c_b^{-1} + c_{ob}^{-1}\,. \qquad (7)$$

If the integrated force resistance will be higher than the maximum possible force of contact with an obstacle, determined by formula (6), the strength of the cabin guaranteed. Our calculations show that upon loading the buffer device when its elements are destroyed, the rigidity in the expression (7) remains constant.

2.5. An algorithm for solving the problem of the construction of the transition to the limit state

Elements of the space Q for the equation (1) can be represented as

$$Q = \{v, m_2, c_{ob}, S_f, \vartheta\}\,, \qquad (8)$$

where S_f — the area of the front of the beam to which the blow falls ($S_f = fS$, S — the whole area, $0 \leqslant f \leqslant 1$), ϑ — the angle of orientation of the obstacle with regard to frontal beam at the moment of impact.

Given the external parameters (8) the cabin survivability is determined by the decision of a number of boundary-value problems that are divided by the conditions the destruction the buffer elements. The cabin buffer device consists of honeycomb elements, the front beam and the fixing beam elements to power rack. At the beginning of the definition of “weak element” boundary problem is solved and the corresponding integral force is determined. Destruction of any element of design leads to a transition from one path to another path load. The new path of loading is determined by the decision of a new boundary problem for the construction in the absence of the damaged element. If the new path has a position of equilibrium corresponding to the previously achieved (before the destruction) value of the load, then the transition to it is possible. One can continue further loading the construction until the destruction of the next element. This design will be survivable. Otherwise, there comes a limit state for the entire cab structure, i. e., a loss of survivability.

3. The results

The implementation of the algorithm for fixed elements Q makes it possible to determine a point on a certain hypersurface of limit cabin states in six-dimensional space (8). A visual representation of the object under study can be obtained only in three-dimensional space, in terms of the most important parameters for a specific situation. Solving problems of calculating the strained state for a number of combinations of external parameters, it is possible to determine an upper bound Γ_q for the set Q. As an example, Figure 1 shows the stress-strain state of cabins under the action of forces uniformly loaded across the front beam ($f = 1$). If we define the boundary of fracture resistance, it is easy to estimate visually the survivability of cabins. In order to visualize a dangerous scenario of a collision with obstacles, Figure 2 shows the boundary (surface) Γ_q corresponding to the equation (4), in three-dimensional space $Q = \{v, m_2, S_f\}$. The other parameters are fixed space with the most probable value $c_{ob} = 0{,}4c_c$, $\vartheta = 90^{0}$. Force of friction between moving obstacles and the ground is neglected. The vertical scale presents the collision speed v in km/h, while the horizontal scale features the mass of obstacles m_2 in kg, on the lateral axis f is the coefficient of coverage area of the front beam. The different curves in Figure 2 correspond to obstacles with different parameters from the stiffness c_{ob} = $0.25 \cdot 10^6$ N/m (the upper dashed line) to c_{ob} = 10^6 N/m (the lower dashed line).

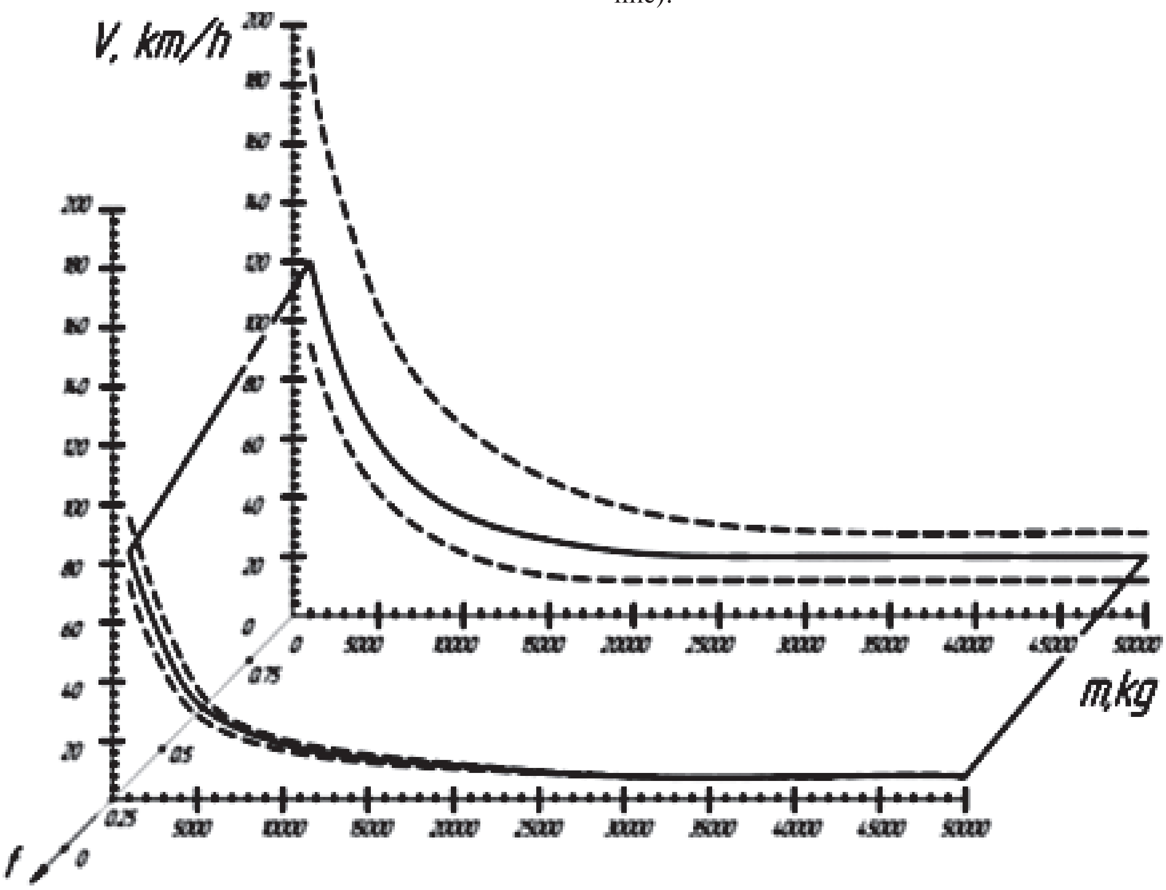

Fig. 2. The boundaries Γ_q of the resistance area for a locomotive cab in three-dimensional space

4. Conclusions

1. The considered cab design ensures the safety of the crew and the equipment in case of the speed limit enforced at a railway crossing, provided that the weight of the obstacles does not exceed 10 tons. It is necessary to strengthen the cab design for the cabin survivability at higher speeds and in a collision with an obstacle of a larger mass.
2. Load application in a limited area of the frontal beams significantly reduces the allowable weight of the obstacles at the permissible speed gas turbine locomotive at a railway crossing. Using Figure 2, on can determine whether the normative speed has been exceeded upon collision with an obstacle of a given mass.
3. It is necessary to strengthen the construction of cabins and buffer device to ensure the safety of the crew and protection equipment and thus to improve the survivability of vehicle.

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